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Study of acoustic wave propagation through the cross section of green wood

Étude de la propagation des ondes acoustiques dans la section transverse du bois vert

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ABSTRACT

An experimental approach was used to model stress wave propagation in green wood (Douglas fir). Based on the assumption that wood is an orthotropic material, the stress wave velocity through the cross section was calculated using plane strain motion equations. The experiments were carried out in two steps under axial restraint, while the wave propagation time was measured on discs and bars sliced from the discs. Mechanical and physical properties were determined in free vibration. The results showed a significant difference in propagation velocity between waves propagating throughout the whole disc volume and guided waves in bars. The acoustic anisotropy of green wood is discussed and the stress wave form simulation is presented. Good agreement between the simulation and experimental results was obtained.

RÉSUMÉ

Dans ce travail une approche expérimentale est utilisée pour la modélisation de la propagation des ondes acoustiques dans le bois vert (Douglas). Le bois est supposé un matériau orthotrope et la vitesse de propagation des ondes acoustiques dans la section transverse est déduite des équations de mouvement pour une déformation plane. L'expérimentation est réalisée en deux étapes sous des conditions d'encastrement, le temps de propagation est mesuré sur des rondelles échantillon et sur des petits barreaux extrait des rondelles. Les propriétés mécaniques et physiques sont déterminées en vibration libre. Les résultats montrent une différence significative entre les vitesses de propagation obtenues sur les rondelles échantillons et celles des ondes guidées dans les barreaux. L'anisotropie du bois vert dans le plan transverse est discutée et la simulation de la forme des ondes est présentée. Un bon accord est observé entre les résultats expérimentaux et simulés.

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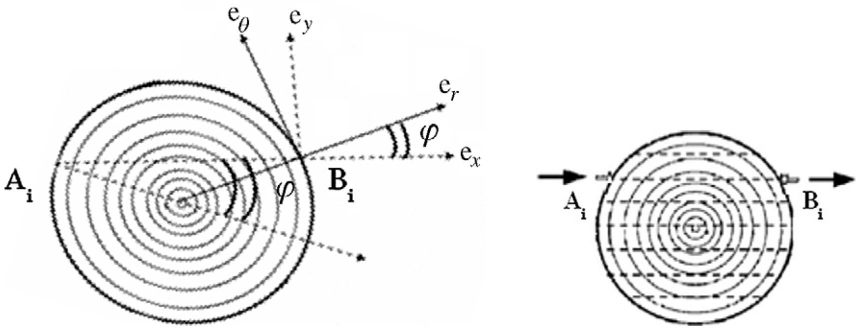

(a) (b)

Fig. 1. Schematic representation: (a) transverse anisotropy; (b) impact tests on whole discs.

1. Introduction

Recently, many researchers have been interested in the development of non-destructive techniques for evaluating wood and wood products. The aim of this research is to identify the physical and mechanical qualities of wood without altering its end-use capabilities. The use of acoustic vibrations to detect decay in wood has been developed for application to logs, utility poles or construction timber, see for example Ouis [1]. The wave propagation velocity, which depends on the square root of the ratio of the elasticity modulus to density, is the most frequently analyzed wave characteristic. Stress wave propagation depends on the grain direction and the excitation. Under certain assumptions this acoustic anisotropy is associated with the mechanical anisotropy, while the anisotropic stiffness parameters can be calculated from acoustic velocity measurements (Bucur et al. [2,3], Brancheriau et al. [4,5]). Acoustic variability in the cross section is of particular interest in acoustic tomography. The anisotropic properties of wood should be taken into account by analyzing stress wave values through the cross section (Bordonné [6], Rin and Kraft [7]). The present study was focused on the interaction between the wood structure and acoustic wave propagation phenomena in the transverse section and on establishing a relationship between the stress wave velocity and the principal directions of transverse anisotropy.

2. Material and methods

A series of experiments were conducted on Douglas fir (*Pseudotsuga menziesi*) wood samples. Trees were cut into logs of 50 to 60 cm length, coated at both ends and stored in water at ambient temperature in order to keep them green. The logs were then sawn into 6 to 7 cm thick disc samples and classified in batches without and with heart rot. Compression stress wave experiments were carried out to simulate the position of the disc samples in standing trees. A restraining system was made with two MDF panels clamped on both sides of the disc sample with two screws. Plastic film was placed between the disc and the panel in order to reduce contact vibration.

The investigation was conducted in two stages under such longitudinal restraint conditions as follows. Stress wave tests were performed by striking one side of the disc with an impact hammer, and the obtained signal was recorded with an accelerometer held in contact with the other side of the disc. The position of each pair of sensors was determined according to the segment (A_iB_i) parallel to the horizontal diameter. Each segment (A_iB_i) was characterized by the angle φ_i (Fig. 1(a)). The impact was performed three times in the direction (A_iB_i) and three times in the direction (B_iA_i) while inverting the position of the emitter and receiver sensor (Fig. 1(b)). The standard deviation due to the wave propagation direction was determined from these multiple measurements. For more details, see Dikrallah et al. [8,9].

3. Results and discussion

The propagation velocity was found to be highly dependent on the rotation angle of the material co-ordinate system. The velocity decreased as the orientation angle increased between 0 and 50° for whole disc volumes and for bars. High stress wave velocity values were obtained for whole discs (see Figs. 2 and 3). The maximum values obtained for the radial direction ranged from 1620 to 1488 m/s. The difference in velocity was about 200 m/s between whole disc volumes and bars. A significant relationship is observed between velocities and the rotation angle. Regression analyses indicated that a second-order ($y = ax^2 + bx + c$) polynomial regression provided the best fit for the experimental data. The coefficients of determination were about 0.98 and 0.95.

This difference can be attributed to the mechanical anisotropy of the wood in transverse section that imposes a curve propagation path. It is well known that the internal properties of the stem cross section determine the path that stress waves travel through wood (Rin and Kraft [7]). The wave-front in our case is perpendicular to the length of the bar, which indicates that the ray path in transverse section is not a straight line. Table 1 shows the results of the statistical analyses performed on the radial axis results (the greatest propagation ray). The error is about 4%.

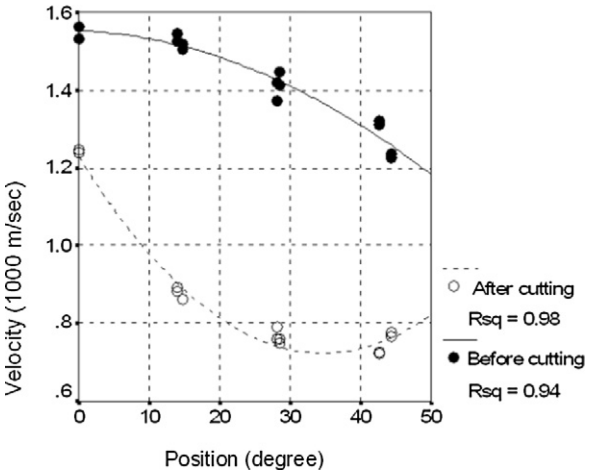

Fig. 2. Relationship between the stress wave velocity and the rotation angle before and after cutting.

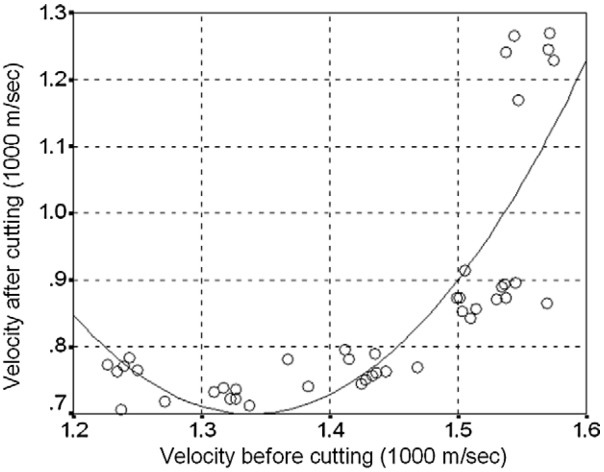

Fig. 3. Stress wave velocity after cutting versus the velocity before cutting.

Table 1
Statistical analyses of stress wave data in the radial axis.

	(A → B) direction		(B → A) direction	
	Travel time (ms)	Velocity (1000 m/s)	Travel time (ms)	Velocity (1000 m/s)
Maximum	0.277	1.595	0.272	1.620
Minimum	0.259	1.490	0.255	1.518
Mean	0.266	1.553	0.264	1.564
Standard deviation	0.006	0.032	0.005	0.031

Fig. 4 shows a statistically significant relation ($R^2 \approx 0.77$) between wave propagation velocities in the two possible propagation directions on discs. This difference can be explained by the fact that the wave did not propagate along the same ray. In the bars, the propagation velocities were the same in both directions. The wave propagated along rays collinear with respect to the main bar axis. A highly significant linear relation was obtained between the wave propagation velocities in both propagation directions ($R^2 \approx 0.97$), thus indicating that $v_{AB} \approx v_{BA}$.

The density variation along the ray showed a linear variation as a function of the distance from the pith. The wet density ranged from 500 to 800 kg/m^3, whereas the dry density was between 300 and 500 kg/m^3 (see Fig. 5). By taking this variability into account, the density radial profile can be approximated over a linear gradient ($\rho = 150(r/R) + 490$).

Based on the assumption that the material is elastic, the velocity of the guided wave is given by square root of the ratio of the modulus to the density, while the equivalent stiffness for wood (orthotropic material) depends on the rotation angle of the material co-ordinate system in the transverse section. The acoustic anisotropy is calculated using an equation of motion for a plane strain. The (E_R, E_T, G_{RT}) parameters are given in Table 2 and compared to theoretical values estimated

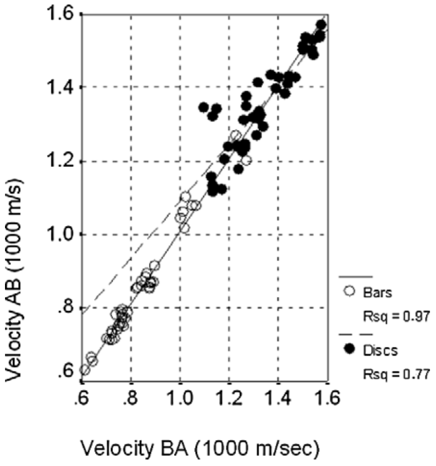

Fig. 4. Relation between propagation velocities in two propagation directions.

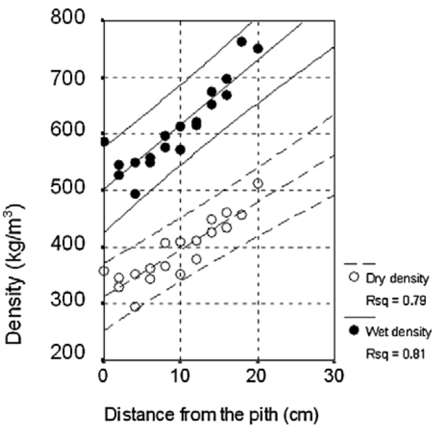

Fig. 5. Wet and dry densities as a function of the distance from the pith.

Table 2
Mechanical properties of Douglas fir wood in free vibration.

	Experimental stiffness (green wood) (MPa)	Theoretical stiffness (MPa)	
		Green	$h = 12\%$; $\rho_{12} = 450$ kg/m^3
E_R	445	449	976
E_T	218	284	617
G_{RT}	33	38	83

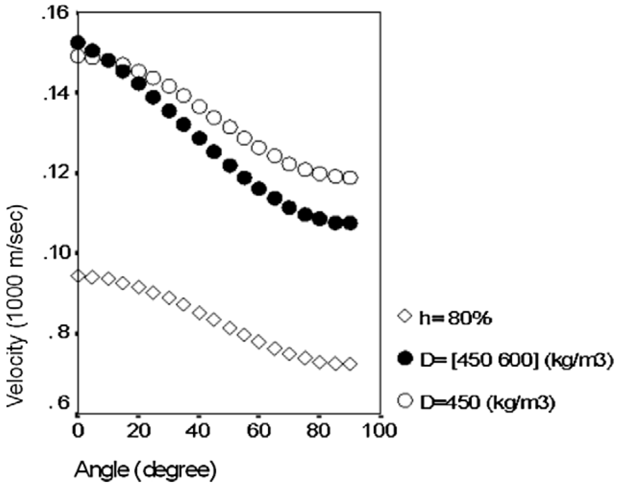

Fig. 6. Stress wave velocity variations with the angular position as a function of density and moisture.

using the two empirical models (density and moisture content) proposed by Guitard [10] for green wood with 12% moisture content. The density value used to calculate the theoretical stiffness was $\rho = 450$ kg/m^3. Little difference was observed between the estimated and experimental values for green wood. Other experimental values can be found in the literature, for example in Refs. [11,12].

The moisture content had a marked effect on the propagation velocity. Conversely, the density gradient did not seem to influence the propagation velocity (see Fig. 6), while the value of the specific elastic component remained almost constant. Fig. 7 presents the propagation velocity pattern according to empirical models of wood behavior as function of the density and moisture (Kollmann and Côté [13], Guitard [14]). Theoretically, the propagation velocity decreases according to the moisture content.

Two theoretical models were developed without taking the moisture content effect and density variation into account. The first one is a propagation model in a bar. The propagation rays are parallel to the symmetry axis of the bar and the second is a propagation model in the transverse section. In Fig. 8, the stress wave velocity is fitted as a function of

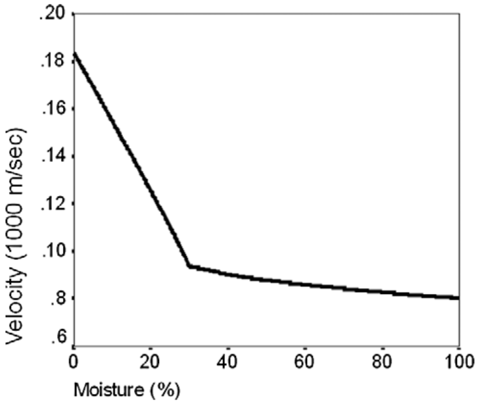

Fig. 7. Theoretical presentation of the stress wave velocity as a function of the moisture content.

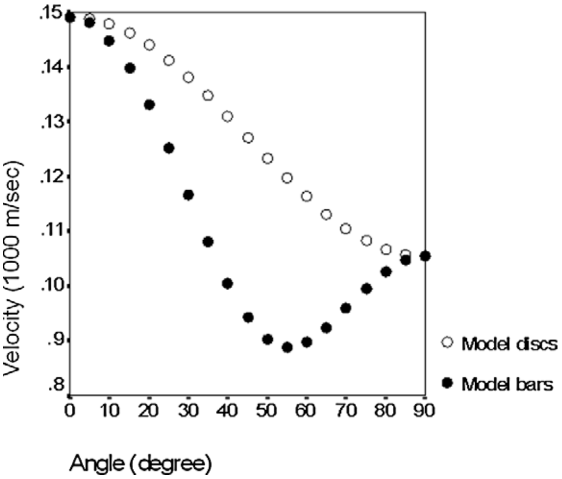

Fig. 8. Theoretical presentation of the stress wave velocity as a function of the orientation angle.

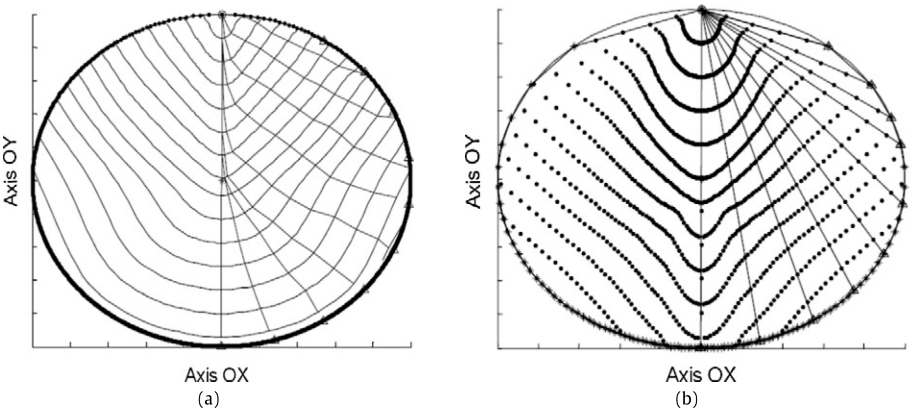

Fig. 9. Propagation models: (a) propagation in cross section, (b) propagation in bars.

the orientation angle φ for standard softwood as reference. We noted, in particular, that the same value was obtained for bars and discs at $\varphi = 0$. In bars the lateral stress was zero, so the radial elastic modulus should be used to calculate the velocity, whereas due to the lateral stress in the disc the value considered should be closer to the radial component of the rigidity tensor. This explains why the prediction in Fig. 8 is closer to the observation in Fig. 2. The simulations $\{(E_{\mathrm{T}}/E_{\mathrm{R}} \approx 0.5)(G_{\mathrm{RT}}/E_{\mathrm{R}} \approx 0.1)\}$ are in agreement with the experimental results given in Fig. 5 for $(0 \leqslant \varphi < 50)$.

The wavefront is computed for each iteration by assuming that the stress wave is quasi-spherical (Coman and Gajewski [15]). This approach involves determining the points M (X_M, Y_M) remote from the impacts O (X_O, Y_O) in the transverse section (R, T) with: $X_M = X_O + V_{xM}t$; $Y_M = Y_O + V_{yM}t$.

In Fig. 9, we represent the wavefront as a function of the position of the point in transverse section. In bars, the propagation ray is parallel to the length. The first wave is on the radial axis and the wavefront is perpendicular to the propagation direction which is parallel to the principal axis of the bar (see Fig. 9(b)). The ray wave is curvilinear in cross section due to the anisotropy that deforms the propagation ray towards the center (see Fig. 9(a)). The wavefront is triangular before reaching the center, and thereafter the wave propagates radially and the wavefront becomes circular.

This phenomenon could be explained by the cylindrical shape of the wood and by the principle of Fermat whereby the wave propagates according to the fastest ray (Shubert et al. [16]). In the case of bars, the ray of propagation is parallel to the length of the bar. The first ray arrives on the radial axis and the wavefront is strictly perpendicular to the ray path (see Fig. 9(a)), the wavefront is triangular after reaching the center. In our case, mean values were used in the simulation since density variations were not taken into account. By using the finite element method, Görlacher [17] showed that the wave face is parabolic and is influenced by the shape of the stem. In summary, the wavefront depends on the frequency and elastic anisotropy of the material.

4. Conclusion

The acoustic behavior of wood in the stem transverse section is a complex phenomenon. The propagation stress wave velocity shows high variability and dependency on the rotation angle of the material in the transverse section. The velocity decreases as the orientation angle increases, which can be explained by the anisotropy of wood. The stress wave velocity in transverse section mainly depends on the stiffness parameters ($E_{\mathrm{R}}, E_{\mathrm{T}}, G_{\mathrm{RT}}$). It seems that the greatest parameter (radial in our case) dictates the propagation direction. The study showed a significant difference between velocities measured in bars and in the associated disk. Velocities are higher in the disk than in bars which imply that waves propagate along curve paths. This last statement was showed by a numerical simulation. The moisture content has a marked effect on the propagation velocity and the density gradient does not seem to influence the propagation velocity. These results will serve as a basis for the application of acoustic tomography to assess wood quality in standing trees.

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